Cold Dark Matter as Compact Composite Objects

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Dark Matter (DM) being the vital ingredient in the cosmos, still remains a mystery. Standard assumption is that the collisionless cold dark matter (CCDM) particles are represented by some weakly interacting fundamental fields which can not be associated with any standard quarks or leptons. However, recent analyses of structure on galactic and sub-galactic scales have suggested discrepancies and stimulated numerous alternative proposals including, e.g. Self-Interacting dark matter, Self-Annihilating dark matter, Decaying dark matter, to name just a few. We propose the alternative to the standard assumption about the nature of DM particles (which are typically assumed to be weakly interacting fundamental point -like particles, yet to be discovered). Our proposal is based on the idea that DM particles are strongly interacting composite macroscopically large objects which made of well known light quarks (or even antiquarks). The required weakness of the DM particle interactions is guaranteed by a small geometrical factor $\epsilon \sim \frac{area}{volume} \sim B^{-1/3} \ll 1$ of the composite objects with a large baryon charge $B \gg 1$, rather than by a weak coupling constant of a new field. We argue that the interaction between hadronic matter and composite dark objects does not spoil the desired properties of the latter as cold matter. We also argue that such a scenario does not contradict to the current observational data. Rather, it has natural explanations of many observed data, such as $\Omega_{DM}/\Omega_B \sim 1$ or $511~KeV$ line from the bulge of our galaxy. We also suggest that composite dark matter may modify the dynamics of structure formation in the central overdense regions of galaxies. We also present a number of other cosmological/astrophysical observations which indirectly support the novel concept of DM nature.

I. INTRODUCTION

Observational precision data gathered during the last fifteen years have guided the development of the so called concordance cosmological model ΛCDM [1] of a flat universe, $\Omega \simeq 1$, wherein the visible hadronic matter represents only $\Omega_B \simeq 0.04$ a tiny fraction of the total energy density. Most of the matter component of the universe is thought to be stored in some unknown kind of cold dark matter, $\Omega_{DM} \simeq 0.24$. The largest contribution $\Omega_\Lambda \gtrsim 0.70$ to the total density is cosmological dark energy with negative pressure, another mystery which will not be discussed here.

There is a fundamental difference between dark matter and ordinary matter (aside from the trivial difference dark vs. visible). Indeed, DM played a crucial role in the formation of the present structure in the universe. Without dark matter, the universe would have remained too uniform to form the galaxies. Ordinary matter could not produce fluctuations to create any significant structures because it remains tightly coupled to radiation, preventing it from clustering, until recent epochs. On the other hand, dark matter, which is not coupled to photons, would permit tiny fluctuations to grow for a long, long time before the ordinary matter decoupled from radiation. Then, the ordinary matter would be rapidly drawn to the dense clumps of dark matter and form the observed structure. The required material is called the Cold Dark Matter (CDM), and the obvious candidates are weakly interacting particles of any sort which are long-lived, cold and collisionless. While this model works very well on large scales, a number of discrepancies have arisen between numerical simulations and observations on subgalactic scales, see [2], [3], [4], [5], [6] and references therein. Such discrepancies have stimulated numerous alternative proposals including, e.g. Self-Interacting dark matter, Self-Annihilating dark matter, Decaying dark matter, and many others, see [4] and references therein. There are many other cosmological/astrophysical observations which apparently also suggest that the standard assumption (that the dark matter made of absolutely stable and "practically non-interacting" fundamental particles) is oversimplified. Some of the observations that may be in conflict with the standard viewpoint are:

• The density profile is too cuspy, [4], [5], [6]. The disagreement of the observations with high resolution simulations is alleviated with time, but some questions still remain [5], [6].

• The number of dwarf galaxies in the Local group is smaller than predicted by CCDM simulations, [4], [5], [6]. This problem is also becoming less dramatic with time [5], [6].

• CCDM simulations produce galaxy disks that are too small and have too little angular momentum, [4], [5], [6];

• There is a close relation between rotation curve shape and light distribution. This implies that there is a close coupling between luminous and dark matter which is difficult to interpret, see e.g. [7];

• There is a correlation in early -type galaxies supporting the hypothesis that there is a connection between the DM content and the evolution of the baryonic component in such systems, see e.g.[8];

• The order parameter (either the central density or the core radius) correlates with the stellar mass in

spirals[9]. This suggests the existence of a well-defined scale length in dark matter haloes, linked to the luminous matter, which is totally unexpected in the framework of CDM theory, but could be a natural consequence of DM and baryon interaction.

• There is a mysterious correlation between visible and DM distributions on $\log - \log$ scale, which is very difficult to explain within the standard CCDM model [10];

• A recent analysis of the CHANDRA image of the galactic center finds that the intensity of the diffuse X ray emission significantly exceeds the predictions of a model which includes known Galactic sources [11]. The spectrum is consistent with hot $8\ KeV$ spatially uniform plasma. The hard X-rays are unlikely to result from undetected point sources, because no known population of stellar objects is numerous enough to account for the observed surface brightness.

We shall argue below that the observed excess of the diffuse X ray emission may be originated from DM component with non- negligible interactions with baryons and photons;

• A recent analysis of the EGRET data finds the intensity of the $GeV\ \gamma$ ray component significantly exceeds the predictions of a model which includes known Galactic sources. More than that, the excess in different sky directions has identical energy spectrum, see e.g. ref.[12] for a nice review of data. This observation strongly suggests that the excess may be originated from DM component with non- negligible interactions with itself or/and with baryons[35].

• The soft gamma-ray spectrum in $1 - 20\ MeV$ region cannot fully be attributed to either Active Galactic Nuclei or Type Ia supernovae or a combination of the two [14]; thus, some sort of "interacting" dark matter particles may be required for a possible explanation for soft gamma-ray spectrum in MeV region;

• Related, but still, a separate issue is the observation of 511 KeV γ-ray line from the bulge of the Galaxy with spherically symmetric distribution [15]. The intensity and some features of the flux are such that it is quite difficult to explain by known astrophysical processes. This observation also strongly suggests that the excess may be related to some sort of DM component with non- negligible interactions with photons.

This list of questions above is obviously very far to be complete. The list of references [2] - [15] (where these questions have been discussed) even less complete. However, the main point we want to make here is as follows: it appears that the DM and ordinary baryons somehow "know" about each other, (beyond the trivial gravitational interaction). Each piece of evidence taken separately is perhaps not convincing enough to abandon the idea that DM is collisionless, non-interacting and absolutely stable weakly interacting massive particle. Nevertheless, it is very likely that some of the problems (mentioned and not mentioned above) persist. In this case it would be an indication that DM is not as trivial substance as it thought to be. In fact, motivated by first

three items above, it has been suggested recently, [2] that DM is actually Self-Interacting dark matter (SIDM) with strength which encompassed the range

$$s = \frac{\sigma_{DD}}{M} \simeq (8 \cdot 10^{-25} - 1 \cdot 10^{-23}) \frac{cm^2}{GeV}, \qquad (1)$$

see also earlier work on the subject [16]. This scale is so similar to the typical cross section for ordinary hadrons at low energies, that it has been even assumed [17] that the DM is composed of exotic hadrons such that interaction between DM particles and ordinary hadrons is the same order of magnitude as given by eq.(1). Many models with such strong interaction of DM with ordinary hadrons are probably already ruled out e.g. from analysis of cosmic rays -DM interactions [18], or from some other constraints.

However, a general idea that DM could be an object strongly interacting with ordinary baryons (in view of many hints coming from very different unrelated observations, see some highlights above) still remains to be a very attractive idea.

In fact, it was recently suggested a natural reason why the dark matter objects might be closely related to the ordinary baryons [19], [20]. Our original argument suggesting the necessity of such kind of connection was based on the observation that $\Omega_B \sim \Omega_{DM}$. Indeed, these two contributions to Ω could be in general very different because (according to the canonical view) they are originated from fundamentally different physics at very different cosmological epoch. Therefore, the observed relation $\Omega_B \sim \Omega_{DM}$ between the two very different contributions to Ω is extremely difficult to explain in models that invoke a DM candidate not related to the ordinary quark/baryon degrees of freedom.

We shall see in what follows, that a resolution of the puzzle $\Omega_B \sim \Omega_{DM}$ within our framework might be linked to a number of other problems highlighted above. We are not claiming, of course, to have these problems solved in our framework. Rather, we want to present some arguments suggesting that many apparently unrelated problems might be in fact closely related.

The idea is that the *dark matter* consists of very dense (few times the nuclear density) macroscopic droplets of *ordinary light quarks* (or/and antiquarks) [19], [20] which however are formed not in ordinary hadronic phase, but rather in color superconducting phase, similar to the Witten's strangelets [21] with mass $M \sim B m_p$, where m_p is proton mass and B is the baryon charge of a droplet. See also [22],[23],[24] where different mechanisms were suggested with potential to explain the observed ratio, $\Omega_B \sim \Omega_{DM}$. See also [25] where composite dark matter was considered, but in a very different context.

Therefore, while the massive droplets carry a large baryon charge $B \gg 1$, they do not contribute to Ω_B, but rather, they do contribute to the "non-baryonic" cold dark matter Ω_{DM} of the universe [19], [20], thus making desirable correlation between DM and baryons as highlighted above.

We should make remark here from the very beginning: while the stability of these objects can be analyzed in relatively simple way with very specific prediction for a given model, the estimation of the probability of formation of such objects is much more difficult task. In particular, the central value for the baryon charge B for the model suggested in [19] is $B \sim 10^{33}$ (it is interesting to note that this value corresponds to $M \sim 10^{33} GeV \sim 10^6$ kg, which is quite close to the existent constraint obtained from analysis of seismic events[26].)

Therefore, we are not attempting to estimate abundance of CCOs in the present work, rather we take an "observational" attitude. Let us assume that such droplets indeed are formed/survived during the QCD phase transition. What would be the observational consequences of this "historical event"? [36].

Our presentation is as follows. In section II we argue that such a scenario does not contradict the current observations. In sections III and IV we put forward this idea, and argue that in fact many puzzles formulated in Introduction can be related to each other within our framework when "Nonbaryonic" dark matter is actually made of strongly interacting *ordinary light quarks* hidden in a *compact composite object (CCO)*.

II. "NONBARYONIC" DARK MATTER AS COMPACT COMPOSITE OBJECT (CCO)

We should emphasize from the very beginning that while our estimates below are based on a specific model [19] for the composite DM, the main concept (and phenomenological consequences) have much more generic applicability.

A. Baryonic CCO –no contradiction with BBN

The main idea is that the baryon charge of massive composite droplets does not change the nucleosynthesis calculations because in the color superconducting phase it is not available for nuclearsynthesis when the baryon charge is locked in the coherent superposition of Cooper pairs (with a typical gap $\Delta \simeq 100\ MeV \gg T_{BBN} \simeq 1\ MeV$). Therefore, while the massive droplets carry a large baryon charge, they do not contribute to Ω_B, but rather, they contribute to the "non-baryonic" cold dark matter Ω_{DM} of the universe, see [19], [20]. In this sense there is a fundamental difference between CCOs and ordinary compact stars (apart from the differences in sizes and formation history): the quarks forming the compact stars did participate in BBN, and therefore they contribute to Ω_B, while the same quarks forming CCOs did not participate in BBN as explained above, and therefore they contribute to Ω_{DM}.

The compact composite objects can be made from antimatter as well, not necessary from matter. Total contribution from these compact composite objects made of antimatter naturally has the same order of magnitude as Ω_{DM}. Still, it would not contradict to BBN due to the same reason: at $T \simeq 1 MeV$ the baryon charge from CCO is not available to participate in nuclear synthesis. Therefore, only baryon charge in hadronic phase can participate in BBN. The baryon (antibaryon) charge hidden in CCO remains unavailable for BBN and serves as DM.

B. Antimatter in the form of CCO. No contradictions with observations

It is important to remark here that bounds that tightly constraint the presence of significant amount of antimatter in the universe are mainly derived from the phenomenological signatures of electromagnetic matter-antimatter annihilation processes [28]. These bounds do not strictly apply to the presence of antimatter stored in CCO as such kind of objects do not easily annihilate. Or to say it more precisely, the rate of annihilation is highly suppressed due to the very small volume occupied by the objects.

Our scenario is based on the idea that while the universe is globally symmetric, the antibaryon charge can be stored in chunks of CCO antimatter. In different words, the baryon asymmetry of the universe may not necessarily be expressed as a net baryon number if the antibaryon charge is accumulated in form of CCO, rather than in form of free anti-baryons in hadronic phase.

Such a picture does not contradict the observations. Indeed, we can estimate the total number of collisions between ordinary hadrons and CCOs in a Hubble time. The number density of hadrons in the ordinary phase is, on average, $n_B \sim \frac{0.15\rho_{DM}}{1GeV}$. Thus, the number of collisions per unit time in presence of a single CCO is given by

$$\frac{d\widetilde{W}}{dt} = 4\pi R^2 n_B v \simeq 4\pi R^2 \frac{0.15\rho_{DM}}{1GeV} v, \qquad (2)$$

where $R \sim M^{1/3} \sim B^{1/3}$ is a typical size of CCOs and $v/c \sim 10^{-3}$ is typical velocity of visible particles. Even if the annihilation is 100% efficient, the total (anti) baryon charge ΔB from anti -CCO which will be destroyed by such annihilations during a Hubble time does not exceed

$$\Delta B \simeq \frac{d\widetilde{W}}{dt} \cdot H^{-1} \leq 0.1 B^{2/3}, \qquad (3)$$

per CCO with charge B. This represents an exceedingly small part of the CCO, $\Delta B/B \sim 0.1 B^{-1/3}$ for sufficiently large B. The probability that CCO will collide another anti CCO during Hubble time is even smaller,

$$\frac{d\widetilde{W}}{dt} \cdot H^{-1} \leq \frac{0.1}{B^{1/3}}. \qquad (4)$$

If one uses already existing constraint on such kind of objects, $B \geq 10^{18}$ [19], or even, $B \geq 10^{30}$ [26], one

concludes that there is no obvious contradiction of the suggested scenario with present observations[20]– DM in form of CCO and anti CCO lives much longer than the Hubble time, and can not be easily destroyed by visible matter[37].

In fact, one can argue that the observed excess of γ ray flux in MeV and GeV bands might be naturally explained from the rare events of annihilation as estimated in eq. (2), see next subsection. Also, the observed cosmological ratio between the energy densities of dark and baryonic matter, $\Omega_{DM} \sim \Omega_B$ within an order of magnitude, finds its natural explanation in this scenario: both contributions to Ω originated from the same physics at the same instant during the QCD phase transition.

Indeed, within our framework the total baryon number is conserved and, therefore, the net number density of CCO droplets should be

$$\widetilde{n}_{\bar{B}} - \widetilde{n}_B = \frac{1}{B}(n_B - n_{\bar{B}}) \simeq \frac{1}{B}n_B, \qquad (5)$$

where we introduce notation $\widetilde{n}_B$ $(\widetilde{n}_{\bar{B}})$ describing the number density of dark matter baryonic (antibaryonic) CCOs which carry the baryon charge in a hidden form rather than in form of free baryons. Let then consider the ratio of *dark matter number density* $\equiv \widetilde{n}_B + \widetilde{n}_{\bar{B}}$ to *baryon number density* $\equiv n_B$. By definition,

$$\left(\frac{dark\ matter\ number\ density}{baryon\ number\ density}\right) \simeq \frac{m_N \Omega_{DM}}{M_{DM} \Omega_B}. \qquad (6)$$

The *dark matter number density* could be naturally estimated, without any *fine-tuning*, to be

$$\widetilde{n}_{\bar{B}} + \widetilde{n}_B = C(\widetilde{n}_{\bar{B}} - \widetilde{n}_B), \qquad (7)$$

where C is some numerical factor $\gtrsim 1$, if the excess $(\widetilde{n}_{\bar{B}} - \widetilde{n}_B)$ is of the same order as the number densities $\widetilde{n}_{\bar{B}}$ and $\widetilde{n}_B$. In fact, the excess $(\widetilde{n}_{\bar{B}} - \widetilde{n}_B)$ is indeed expected to be of order $\widetilde{n}_{\bar{B}}$, $\widetilde{n}_B$ if the universe is largely C and CP asymmetric at the onset of formation of the condensed balls. Then, the l.h.s. of the ratio (6), can be estimated to be

$$(\widetilde{n}_{\bar{B}} + \widetilde{n}_B)/n_B = C(\widetilde{n}_{\bar{B}} - \widetilde{n}_B)/n_B \simeq \frac{C}{B} \qquad (8)$$

according to eqs. (5,7). Consequently, from (6,8) we obtain

$$\Omega_{DM}/\Omega_B \simeq (C/B) \cdot (M_{DM}/m_N). \qquad (9)$$

Now, if one demands $B \simeq (M_{DM}/m_N)$, which is a condition for the stability of the droplets [19], one can immediately derive $\Omega_{DM}/\Omega_B \simeq C \gtrsim 1$. The point we want to make is: our assumption that the dark matter is originated at the QCD scale from ordinary quarks fits very nicely with $\Omega_{DM}/\Omega_B \gtrsim 1$ within the order of magnitude, provided that separation of baryon charges is also originated at the same QCD scale. Generally, the relation $\Omega_B \lesssim \Omega_{DM}$, within one order of magnitude, between the

two different contributions to Ω is extremely difficult to explain in models that invoke a dark matter candidate not related to the ordinary quark/baryon degrees of freedom. The baryon to entropy ratio $n_B/n_\gamma \sim 10^{-10}$ would also be a natural outcome in this scenario. We refer to the original paper [20] for the details.

C. Annihilating CCOs. No contradictions with γ ray flux observations

The DM in form of CCO, in some sense, has some features of annihilating DM[29] as baryon charge from visible matter and antibaryon charge from anti CCOs do annihilate as discussed above. Naively, one could think that large amount of antimatter (order of Ω_{DM}) is already in severe contradiction with γ ray flux observations. Indeed, in order to avoid the contradictions with γ ray flux observations, the authors of the annihilating DM proposal [29] have assumed that annihilation products must not include photons. In our scenario when DM is represented by ordinary quarks/antiquarks we do not have a luxury to make such kind of assumptions because ordinary quarks and anti quarks do annihilate and do produce photons. However, as we shall see, when DM is locked in CCOs still there is no contradiction with γ ray flux observations. In fact, such annihilation might be a natural solution of a long standing problem on observed γ ray excess in MeV and GeV bands. By definition, the flux is defined as

$$\Phi = \int ds \int_{\Delta\Omega} d\Omega \frac{dW}{dVdt}(r), \qquad (10)$$

where $\frac{dW}{dVdt}(r)$ is the probability of the annihilation event per unit volume per unit time at point r measured from the center of the galaxy, $\Delta\Omega$ is the solid angle observed, and the integral $\int ds$ is performed over the line of sight of the observation. The probability of annihilation can be estimated as in eq.(2),

$$\frac{dW}{dVdt}(r) \simeq 4\pi R^2 \cdot v \cdot n_B(r) \cdot n_{DM}(r) \simeq$$
$$4\pi R^2 \cdot v \cdot \left(\frac{\rho_B(r)}{1GeV}\right) \cdot \left(\frac{\rho_{DM}(r)}{B \cdot 1GeV}\right) \sim B^{-1/3}, \qquad (11)$$

where we assume that annihilation is 100% efficient such that all baryons hitting the CCOs will annihilate. One can check that estimate for the flux (10) with $\frac{dW}{dVdt}(r)$ given by eq. (11) is not in contradiction with observations for sufficiently large B[38]. This is the main massage of this subsection.

Rather than making constraints on B it is very tempting to assume that the excess of $511KeV$ photons [15] as well as γ -excess in MeV [14] and GeV bands [12] as highlighted in Introduction, can be explained precisely by this annihilation with dark matter in form of CCOs. In fact, all features of $511KeV$ line from the bulge of our galaxy (including the width, spectrum and intensity) can

be naturally explained by using eq. (11) and accepting the standard distributions for the dark and visible matter when $B \sim 10^{33}$ [30]. Once the general normalization is fixed from the observation of $511 KeV$ line, one can unambiguously predict the flux integrated over photon's spectrum in MeV region originated from annihilation of visible matter with dark matter in form of CCOs[31]. Corresponding calculations are beyond the scope of the present work; however, the obvious consequence of the scenario is that the flux in MeV range and $511 KeV$ line must be strongly correlated in all sky directions. Unfortunately, available data (see [14] and references therein) are not sufficient to make a positive statement on this. However, what is known is definitely consistent with this prediction. We also point out that e^+e^- annihilation with a single bright $511 KeV$ line should be accompanied by the wide (70 MeV -1 GeV) γ spectral density due to the annihilation of baryon from visible matter with anti baryonic charge from dark matter in form of CCOs. These very different spectra in different frequency regions must be related to each other due to their common origin. Corresponding calculations are beyond the scope of the present work; however, a very simplified estimate of the corresponding flux can be obtained by replacing electron velocity v in formula (11) by a proton velocity $v_p/v \sim \sqrt{m_e/m_p} \sim 2 \cdot 10^{-2}$[30]. This corresponds to the assumption of the thermal equilibrium between electrons and protons in the ionized region in the bulge of the galaxy. Estimated in such a way flux is consistent with observations, where some access of γ rays indeed has been observed by EGRET, see [12] and references therein.

D. Photon - CCO decoupling. No contradictions with structure formation constraints

As we discussed in previous subsections, the interaction between dark matter in form of CCOs and photons is quite strong. Therefore, a natural question arises whether such an interaction does not spoil the main feature of the DM, and whether the compact composite objects of condensed quark matter do indeed qualify as candidates for the role of cold dark matter of the universe at the time $T_{eq} \lesssim 1$ eV when large scale structures develops. Such interaction, in principle, could spoil the desired non-thermal distribution of dark composite objects. However, as we shall estimate below, sufficiently large CCOs do indeed qualify as cold dark matter candidates.

First, we recall why ordinary matter can not play a crucial role in structure formation. This is due to the fact that the baryons are tightly coupled to the photons until decoupling time, $z_{Dec} \simeq 1100$, $T_{Dec} \simeq 0.26 eV$. This tight coupling provides the baryonic fluid with a pressure which prevents the small perturbations to grow due to the force of gravity.

Indeed, at $t \ll t_{Dec}$ photons and baryons are very tightly coupled due to Thomson scattering. The mean free time

$$t_{Th} = \frac{1}{x_e n_B \sigma_{Th} c} \simeq 6 \cdot 10^7 s \left(\frac{T}{1eV}\right)^{-3} \left(x_e \Omega_B h^2\right)^{-1} \quad (12)$$

with x_e being the fraction of charged particles, and $\sigma_{Th} = \frac{8\pi}{3}(\frac{e^2}{m})^2$ being the Thomson scattering cross section, should be compared with Hubble time

$$H^{-1} \simeq 1.13 \cdot 10^{12} s \left(\frac{T}{1eV}\right)^{-3/2} \left(\Omega h^2\right)^{-1/2}, \quad t > t_{eq}. \quad (13)$$

The condition $t_{Th} \ll H^{-1}$ is obviously satisfied when $x_e \sim 1$ before the recombination.

We now estimate the interaction between dark matter in form of CCOs and photons. As before, we assume that the cross section is proportional to the geometrical size, $4\pi R^2$ such that the relevant mean free time is

$$t_{DM} = \frac{1}{4\pi R^2 n_{DM} c} \simeq \left(\frac{T}{1eV}\right)^{-3} \left(\frac{4 \cdot 10^9 B^{1/3}}{\Omega_{DM} h^2}\right) s. \quad (14)$$

It is clear from this expression that for sufficiently large $B \gg 1$ the condition $t_{DM} \gg H^{-1}$ is obviously satisfied, and therefore, CCOs do indeed qualify as candidates for the role of cold dark matter.

E. Generic feature of CCO– effectively weak interaction as geometrical factor

The main message of Section II can be formulated as follows. We observed that there are no any contradictions with observations if DM is represented by macroscopically large composite compact objects made of ordinary matter or even antimatter, as described above. The main reason why this very counterintuitive concept still does not contradict the observations has pure geometrical nature. Indeed, the effective interaction which appears in all previous discussions is proportional to a factor, $\epsilon \sim \sigma \cdot n_{DM}$ which can be represented in pure geometrical terms describing a composite objects $\epsilon \sim S/V$. Indeed, a typical scattering cross section off a large macroscopical object is always proportional to its surface area, $\sigma \sim S \sim B^{2/3}$, while number density of heavy DM particles, $n_{DM} \sim \rho_{DM}/M \sim V^{-1} \sim B^{-1}$ is proportional to the inverse volume of the composite objects filled by quarks, $M \sim V \sim B$. Therefore, for macroscopically large composite objects this ratio $\epsilon \sim \sigma \cdot n_{DM} \sim S/V \sim B^{-1/3} \ll 1$ could be numerically very small if number of particles B forming the object is very large. This small geometrical factor $\epsilon \ll 1$ can successfully replace the standard assumption on weak coupling interaction between visible and DM. As it is known, this requirement is a crucial ingredient of entire idea of DM as a substance which is collision-less and weakly interacting. Our remark here is: the weakness of the interaction can be achieved by a new concept of compact composite objects with $\epsilon \ll 1$

instead of introducing into the theory some new, not yet discovered weakly interacting massive particles (such as WIMPs).

III. THERMODYNAMICS

The main goal of the previous section was to argue that CCO is qualified as a cold dark matter candidate. More precisely, we argued that a new concept of compact composite objects does not contradict to any observations and does not spoil any standard requirements which are crucial for the structure formation. Therefore, naively one should not expect any differences in behavior between CCOs and let us say, the standard WIMPs as far as structure formation is concern [39]. Nevertheless, we shall argue below that the ability of CCOs to interact efficiently with photons and hadrons, unlike fundamental point-like particles, is a new distinctive feature which might have phenomenologically observable consequences relevant for the structure formation at smaller scales. Hopefully, it may even lead to the resolution of some problems highlighted in the Introduction. This new feature of CCOs provides a mechanism that, in principle, has ability to modify the structure formation in the central denser regions where the interaction of visible hadrons/photons with internal degrees of freedom of CCOs can reach thermal equilibrium.

Let us emphasize, we are not talking about thermal equilibrium between CCO as a whole object and visible matter. There is no such equilibrium, as we demonstrated previously. It should not be such an equilibrium according to the standard requirement of the structure formation theory. Rather, we are talking about thermal equilibrium between visible matter and *internal degrees of freedom* of a compact composite object.

A. Idea

The picture that we have in mind is similar to the interaction of molecules of air with the internal excitations of a solid lattice, the phonons. Phonons can be, in good approximation, be described as massless degrees of freedom in thermal equilibrium with surrounding environment at the same room temperature T. Obviously, this interaction is unable to keep the whole massive solid in thermal equilibrium with the molecules of the gas. The crucial point here is that most of the mass of the solid is carried by the atoms that form the lattice, while the mass of vibrational excitations is orders of magnitude lighter.

Following this example, we consider a statistical ensemble of dense massive droplets surrounded by a gas of much lighter hadrons. The typical mass of the droplet $M \simeq B m_N$, where B is the baryon number carried by the droplet and m_N is the mass of the nucleon. The baryon charge B can be very large. In particular, for the formation mechanism suggested in ref. [19], the typical

$B \sim 10^{33}$. However the discussions which follow have much more generic applicability and are not limited by specific model considered in [19]. Therefore, in what follows we consider an arbitrary compact composite object filled by quarks and gluons (in color superconducting or any other phase) which can be treated as a CCO containing a gas of massless goldstone modes in thermal equilibrium with the surrounding gas of visible hadronic matter. Precise condition when such thermal equilibrium can be maintained is formulated below.

The key point is as follows: the internal degrees of freedom of cold composite objects being in thermal equilibrium with hadrons store a new *hot* contribution to the total matter density. One can call such dark matter a *"chameleon- like DM"* because its properties strongly depend on environment surrounding it. It has all features of ordinary cold DM in the very dilute environment; it becomes hot in the environment when the ordinary visible matter becomes very dense, and thermal equilibrium of internal degrees of freedom with visible matter can be maintained. To say it differently, the heat stored in CCOs can be transfered to visible matter if it is sufficiently dense, see precise qualitative relation below. Therefore, the DM in form of CCOs may change the standard picture of the dark matter distribution at small scales when the visible matter becomes very dense, such as it happens at the center of galaxies.

B. Thermodynamics of the internal degrees of freedom in the compact composite objects

To be precise, we say that the local thermal equilibrium of internal degrees of freedom of a compact object with visible hadrons is maintained at temperature T^* [40] if the number of baryons hard-hitting a single CCO during the Hubble time greatly exceeds the number of internal excitable degrees of freedom of this composite compact object. This condition can be expressed in a formal way as follows,

$$(n_B \sigma v) \times H^{-1} \gg \int_V e^{-\frac{p}{T^*}} \cdot \frac{d^3 p d^3 x}{(2\pi)^3}, \qquad (15)$$

where combination $(n_B \sigma v)$ determines the total number of collisions of visible hadrons per second with a single compact object with a typical size R. In this formula we present n_B as follows, $n_B \sim \xi \overline{\rho}_B / m_N \sim \xi \overline{\rho}_B / \rho_c \cdot 10^{-5} h^2 cm^{-3}$; parameter ξ in this expression is $\xi \equiv \rho_B / \overline{\rho}_B \gg 1$ and it describes the excess of the local baryon matter density ρ_B (e.g. in galaxies) in comparison with the averaged density over entire universe $\overline{\rho}_B$. In formula (15) we estimate the number of internal massless degrees of freedom (such as phonos) of a CCO assuming a simple Boltzmann distribution, neglecting many complications related to the specific structure of the compact objects, such as presence of a condensate, spin of the Goldstone particles etc. For numerical estimates we take $\sigma = 4\pi R^2$ and $B \sim 4\pi R^3 n_0 / 3$ where $n_0 \sim (108 MeV)^3$ is

nuclear density. Assuming the equilibrium as formulated above, we estimate a typical velocity v for the visible hadrons as $v/c \sim \sqrt{2T^*/m_N}$. Having done all these simplifications we arrive to the following numerical estimate for the visible matter density ρ_B when the local thermal equilibrium of internal degrees of freedom of the composite compact objects can be maintained with visible hadrons in the dense environment at temperature T^*,

$$\xi \left(\frac{10KeV}{T^*}\right)^{5/2} \gg 10^4 \left(\frac{B}{10^{33}}\right)^{1/3}, \ \xi \equiv \rho_B/\overline{\rho}_B. \quad (16)$$

C. Immediate consequences

The obtained relation (16) is very suggestive, and it definitely deserves some additional comments. First of all, if we interpret sign $\gg$ in eq. (16) as factor ~ 10 or so, the relation (16) predicts that unusual features of the dark matter (assuming it is made of CCOs) start to show up at densities where $\xi \sim 10^5$. Amazingly, this value of ξ precisely corresponds to a typical matter density at kpc scales where the standard N body ("cuspy") simulations apparently start to deviate from observational data. Therefore, it is tempting to interpret this result as manifestation of dark matter features (there existence of internal degrees of freedom hidden in CCOs) which are not taking into account in the standard N body simulations. We shall present few more arguments supporting this interpretation in the next section.

Another interesting scale in this formula is $T^* \sim 10~KeV$ when density ξ approaches its typical galactic value $\xi \sim 10^5$. Why $T^* \sim 10~KeV$ is so special? We would like to interpret this temperature $T^* \sim 10~KeV$ as a hot component of plasma which was the crucial ingredient in the recent fitting of the diffuse X-ray emission from the Galactic Center[11]. This is one of the problem highlighted in the Introduction. According to ref. [11] the spectrum is consistent with a two-temperature plasma with the hot component close to $T \simeq 8~KeV$. According to analysis [11] the hot component is very difficult to understand within the standard picture. First of all, it would be too hot to be bound to the Galactic center. Authors of ref. [11] also remark that the energy required to sustain such plasma corresponds to the entire kinetic energy of one supernova every 3000 yr, which is unreasonably high. Finally, authors conclude with the following pessimistic note: "We are left to conclude either that there is a significant shortcoming in our understanding of the mechanisms that heat the interstellar medium or that a population of faint hard X-ray sources that is a factor of 10 more numerous".

It is very tempting to interpret this result as follows. The missing sources of the required heat are stored in the form of internal degrees of freedom of CCOs as discussed above. This interpretation is entirely based on a new concept of the dark matter when excitable internal degrees of freedom of CCOs and visible hadrons can be in the local thermal equilibrium. This only can happen when the visible matter density is sufficiently large(16). The interpretation suggested here is not sensitive to the specific details of our model. Instead, the consequences described above are very generic features of any dark matter substance if it is represented by the large compact composite objects rather than by some point like particles such as WIMPS.

IV. OTHER CONSEQUENCES

Our new concept of the dark matter is no doubt lead to many other important consequences for cosmology and astrophysics, which are not explored yet. We highlighted some of the problems (which can not be easily understood within the conventional CCDM paradigm) in the Introduction. Those problems may have some relation to the dark matter nature as we advocate in the present work.

• In particular, we already mentioned in Section IIC that excess of photons in MeV and GeV bands as well as 511 KeV line from the Galactic Center may have natural explanation if DM is consist of chunks of massive droplets. We also mentioned in Section IIIC that unusual features (such as intensity and spectrum) of the diffuse X ray emission from the galactic center may also have a natural explanation if DM is consist of chunks of massive droplets.

Here we want to discuss some other issues related to *DM $\Leftrightarrow$ Baryons correlations* which apparently have been observed in many different instances, see few highlights in the Introduction. While such correlations are quite natural outcome in our framework, see below, the same correlations look very mysterious and difficult to understand within the conventional Collisionless CDM paradigm. But first, we want to make few general remarks to emphasize the fundamental differences between our concept of the dark matter and the conventional viewpoint when the DM is represented by fundamental point-like particles like axion, neutralino, or other WIMP candidates.

By definition, cold dark matter must have decoupled from the thermal plasma of hadrons, electrons and photons before recombination, so that it can gravitationally collapse in the characteristic triaxial virialized halos that drove the formation of large scale structures. We argued in Section IID that indeed the dark matter in form of CCOs does satisfy this requirement. This generic description trivially proves that there can exist a component of dark matter in internal degrees of freedom which is hot in the sense that is in thermal equilibrium with hadrons, but it contributes zero pressure to the cosmic plasma because it is confined inside the massive and macroscopic cold droplets of condensed quarks. Evidently, such component is absent if DM is represented by any fundamental point-like particles like axion, neutralino, or other WIMP candidates.

We have seen that supermassive CCOs can be perfect candidates for the role of cosmological cold dark matter during the process of structure formation, as they never reach thermal equilibrium with the surrounding hadrons even if there is efficient transfer of energy between the latter and the internal degrees of freedom of the former. This feature is quite unique and it is not shared by any other DM candidates. The gravitational collapse of the supermassive composite objects shall successfuly reproduce over large cosmological scales the characteristic features of the web of hierarchichal CDM structures. On the other hand, within the overdense central regions of structure formation thermal equilibrium between hadrons and massless internal modes of composite objects can be reached and the interaction can modify the dynamics of the structure. According to condition (16), these regions roughly correspond to the sub-galaxies scales where matter density is at least $\xi \gtrsim 10^5$ higher than the cosmological average. This condition roughly defines the inner core of galaxies where collissionless cold dark matter models fail to reproduce the high resolution features of the observed structures [5].

• We anticipate that at this small scales when density is large, $\xi \gtrsim 10^5$ the internal degrees of freedom of CCOs will heat up the low entropy material, which would lead to additional pressure in overdense regions. This interaction would result in formation of a core rather than a cusp; it will also produce a shallower density profile; the centers of halos are expected to be spherical (rather than triaxial) due to the same interactions. At the virial radius of a typical galactic halo where overdensity is much smaller, $\xi \ll 10^4$, the condition (16) is not satisfied any more, and therefore, the usual, triaxial cold dark matter halo will result at these larger scales. In many respects these results are very similar to the predictions which follow from strongly interacting DM models [2], [3], [4]. The microscopical nature of the interactions in these two cases, of course, is very different. At the same time other predictions (described in the next item) are not shared by strongly interacting DM models [2], [3], [4].

• We also anticipate (due to the interaction of visible matter with dark matter in our framework) some correlations between DM and visible matter distributions. Intriguingly, a number of different observations (see e.g. refs. [7],[8],[9]) apparently do support such correlations. In particular, in ref.[7] it is argued that "there is a close correlation between rotation curve shape and light distribution. For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa". Similarly, in ref. [8] it was argued that the dark matter has triggered the evolution of both the stellar and hot gas components in galaxies. Very different analysis [9] reaches very similar conclusion "that the galaxies ... are uniquely successfully fitted by cored haloes, with a core size comparable to the optical radius. This suggests the existence of a well-defined scale length in dark matter haloes, linked to the luminous matter, which is totally unexpected in the framework of CDM theory". Our re-

mark here is as follows: all these observations which apparently are hinting on DM $\Leftrightarrow$ Baryons correlations, are difficult to understand within the standard framework of collisionless CDM. In contrast, the same results may have very natural explanation if dark matter is represented by droplets with excitable internal degrees of freedom when condition (16) is satisfied, in which case the DM and visible matter distributions must be obviously correlated.

• The same interaction between DM and Baryons can be also responsible for the resolution of the angular momentum problem. Indeed, such an interaction can prevent the visible gas from overcooling, which is considered to be the main cause of the angular momentum problem transfer[5].

• Analysis of ref.[10] also finds the visible and dark matter correlations. This claim was supported by the fitting of the dark matter vs visible matter distributions on the $\log - \log$ plot. The linear dependence between the two components was interpreted as an evidence of the thermal (or hydrodynamical) equilibrium between the visible and DM components. While complete understanding of this "accidental correlation" is obviously missing, the results of ref.[10] are quite encouraging from the viewpoint advocated in this work when the internal degrees of freedom of droplets indeed can be in the thermal equilibrium with visible matter in overdense regions. It is expected that the correlations would persist even at much larger scales after the freeze-out (decoupling) takes place.

It is quite amazing that the effective temperature extracted in ref.[10] turns out to be of the same order of magnitude as our estimate (16) with $T^* \simeq 10 KeV \sim 10^8 K$. As we mentioned in Section IIIC precisely such temperature is required to fit the data on diffuse X ray emission from the galactic Center[11]. Another intriguing result of the analysis ref.[10] is the estimation of value for the dark matter particle mass (300 MeV) which is astonishingly close to the typical QCD scale. While we do not think that this value corresponds to any fundamental particle mass, we still expect that such numerical value is not an "accidental coincidence" of the analysis but rather is the result of the QCD dynamics in the bulk of the compact composite objects.

To conclude this section and to avoid the misunderstanding: we are not claiming to have resolved all the problems highlighted in the Introduction (and discussed in this section). Rather, we wanted to present some arguments suggesting that many seemingly unrelated problems might be in fact closely related if we accept the new concept of DM nature which assumes that dark matter particles to be represented by compact composite objects formed during the QCD phase transition.

V. CONCLUSION. FUTURE DIRECTIONS.

We conclude with few general remarks and few suggestions for the future work. The main goal of this work

was twofold. First, we argued that the new concept of the dark matter when it is represented in the form of macroscopically large compact composite objects (with excitable internal degrees of freedom), does not contradict to any current observations. Secondly, this new concept has a potential for the natural explanations of many phenomena which are difficult to explain within the standard paradigm. Each piece of evidence taken separately is not convincing enough to abandon the idea that DM is collisionless, non-interacting and absolutely stable weakly interacting massive particle. Nevertheless, it is very likely that some of the problems discussed in this work would persist. In this case a new concept of DM nature must be developed, and this work offers one of the possibilities.

Unlike fundamental point-like cold matter particle, the compact composite objects (CCOs) do interact with visible hadrons quite efficiently in the dense environment (16) by exciting the internal degrees of freedom confined to the bulk of CCOs. As we argued it does not spoil the coldness of CCOs. The internal modes represent a *hot* contribution to the total dark matter density that, nevertheless, contributes zero pressure to the cosmic fluid.

Over the large cosmological scales the interaction is mostly irrelevant because matter, both visible and dark, is too sparsely distributed to keep thermal equilibrium(16). As a consequence of it, the massive composite dark matter droplets shall produce a web of cosmic structures with the characteristic large scale hierarchichal features succesfully reproduced by any model of cold dark matter. On the other hand, within the overdense core regions of structure formation the visible hadrons can efficiently interact with composite dark matter objects, and reach thermal equilibrium.

• This feature can change the dynamics of the structure in its central denser region satisfying eq. (16) as argued in Chapter IV. We presented a number of qualitative arguments supporting this claim. It is obvious: only numerical simulations can confirm or rule out the phenomena we predicted above. The crucial new element of such simulations should be a modeling /incorporation of the interaction of visible matter with internal degrees of freedom of the large droplets. Therefore, we strongly advocate to perform such an analysis to see whether the new phenomena anticipated in Chapter IV indeed take place.

• As we mentioned earlier there are many other important phenomena in cosmology and astrophysics, which are not explored yet, and which may be also influenced by the new concept of DM as composite objects. In par-

ticular, as was argued previously[19],[20] and reviewed in section IIB there existence of droplets made of anti-matter does not contradict to any current data, but rather may provide a natural explanation of the observed ratio $\Omega_{DM} \sim \Omega_B$. At the same time the rare events of annihilation of such droplets could distort the CMB anisotropies and polarization as first discussed in ref.[32]. Also: if we accept the explanation of 511 KeV line and excess of photons in 1 GeV band as due to the annihilation of visible matter with anti matter droplets[30], than there must be a correlation between 511 KeV flux distribution, 1 GeV photons and CMB anisotropies[33].

One more observational consequence: If the picture advocating in this work is indeed correct, then the DM isodensity contours should become more and more circular (or at least follow more and more closely the baryon distribution) at smaller radius. That's something one can hope to measure with galaxy-galaxy lensing[41]. One should not expect such a behavior if DM particles are ordinary WIMPs.

It could be many other observable consequences of this new concept on nature of DM which are still to be explored.

Latest Notes Some aspects of this framework (when dark matter is represented in the form of CCOs) have been recently criticized by Cumberbatch, Silk and Starkman[34]. We refer to our reply [31] on this criticism where it is explicitly shown why the arguments presented in[34] are incorrect.

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[35] One should remark here that the interpretation of the same data could be very different: the agreement with EGRET data can be achieved by assuming a specific variation of cosmic rays intensity in space and time. It also requires some adjustments of the spectrum of cosmic rays at low energies. This subject is still matter of debates and we refer to the original literature for details [13].

[36] The corresponding analysis on formation of the macroscopically large objects is expected to be very complicated problem. In particular, it would require knowledge of the non equilibrium dynamics of the QCD phase transition at nonzero baryon density $\mu \neq 0$ and nonzero value of parameter $\theta \sim 1$ which is essential element for the mechanism to be operative as discussed in [19]. Unfortunately we have very limited knowledge about the QCD phase diagram when these parameters are non-zero. The first steps in the study of the QCD phase diagram at $\mu \neq 0$ and $\theta \sim 1$ (with motivation from cosmology) have been undertaken only very recently[27]. Nevertheless, few arguments (supporting the idea that indeed a separation of baryon and anti baryon charges during the QCD phase transition at $\mu \neq 0$ and $\theta \sim 1$ is possible if some conditions are met) have been presented in ref. [20]. The most important lesson from this study was that if small droplets are formed (as a result of fluctuations), they start to grow due to the differences of reflection and transmission coefficients for quarks and antiquarks at $\theta \neq 0$: CCOs made of matter prefer to capture quarks/baryons while CCOs made of antimatter prefer to capture antiquarks/antibaryons. The difference in coefficients is order of one, therefore the growth of CCOs is extremely efficient. However, even it is 100% effecient, some baryons along with CCOs would still remain in our universe because of the large CP violation at that time (equal number of CCOs made of matter and antimatter when no baryons left would correspond to the exact CP symmetric case). This process of formation continues until temperature becomes sufficiently small ($T \sim 40$ MeV) when gas of particles becomes sufficiently dilute, and their energies are relatively low to penetrate into the droplets. It is expected that the difference in numbers of CCOs made of quarks and antiquarks will be order of one due to the strong CP violation at that time. This is exactly the main reason why $\Omega_{DM} \sim \Omega_B$, see eq. (9). Precise calculation of $T \sim 40$ MeV represents a very difficult problem of the non equilibrium QCD. However our estimates presented in ref. [20] strongly suggest that it falls into the appropriate energy scale. As we said in the text, in the present work we just take a simple "observational attitude" formulated as follows: let us assume that such droplets indeed can be formed during the QCD phase transition. What would be the observational consequences of this "historical event"?

[37] An obvious question is: what happens when a CCO hits the Earth. By obvious reasons this question was addressed earlier, in the first original paper on the subject [19]. The only comment we would like to make here is as follows. Due to the gap in color superconducting phases the vast majority of slow non relativistic particles will be reflected when they hit CCO. It is equally true for matter as well as for antimatter. Therefore, phenomenological consequences of such an event would be

very similar to what have been discussed previously for the Witten's droplets. It is expected that such an event would produce a line like seismic event in contrast with conventional point like events due to the earthquakes, see ref. [26] for the detail discussions, latest constraints and earlier references.

[38] Precise constraint on B depends on specific model for $\rho_{DM}(r)$ and $\rho_B(r)$.

[39] Of course, there is distinctive feature between CCOs and other DM candidates for other observables, such as emission 511 KeV line, as we discussed in previous section.

[40] do not confuse T^* with the temperature describing the evolution of the entire universe T.

[41] I am thankful Ludvic Van Waerbeke for suggesting such measurements as a possible test of DM as compact composite objects.